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Wireless Sensor Networks for Early Detection of Forest Fires

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Motivations

- **Forests cover large areas of the Earth, home to many animals and plants**
- **Numerous forest (wild) fires occur every year**
  - **Canada: 4,387 fires/year (average over 10 years)**
  - **USA: 52,943 fires/year (average over 10 years)**
  - **Source: Canadian Forest Service**
- **In some cases, fires are part of the ecosystem**
  - **But in many others, they pause a threat to human lives, properties, infrastructure, …**

Motivations (cont'd)

- Example: August of 2003
- A fire in Okanagan Mountain Park, BC, Canada→
  - 45,000 residents evacuated
  - 239 homes burned
  - 25,912 hectares burned
  - 14,000 troops and 1,000 fire fighters participated
  - $33.8 millions total cost

  - Source: BC Ministry of Forests and Range

Motivations (cont'd)

- To limit damages of a forest fire, early detection is critical
- Current Detection Systems
  - Fire lookout tower (picture)
    - Manual ➔ human errors

  - Video surveillance and Infrared Detectors
    - Accuracy affected by weather conditions
    - Expensive for large forests
  - Satellite Imaging
    - Long scan period, 1-2 days ➔ cannot provide timely detection
    - Large resolution ➔ cannot detect a fire till it grows (>0.1 hectares)

Our Problem

- **Design and evaluate a wireless sensor network (WSN) for early detection of forest fires**

- **WSN is a promising approach**
  - **Various sensing modules (temp., humidity, …) available**
  - **Advances in self-organizing protocols**
  - **Ease of deployment (throw from an aircraft)**
  - **Mass production → low cost**
  - **Can provide fine resolution and real-time monitoring**

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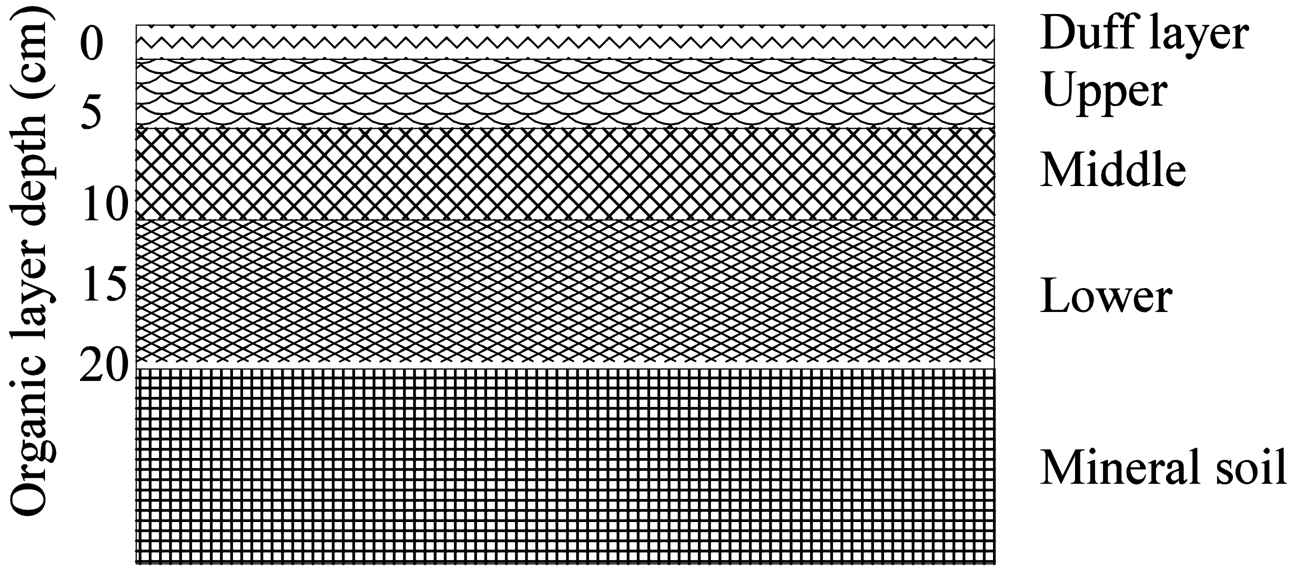
Our Approach and Contributions

- **Understand key aspects in modelling forest fires**
  - **Study the Fire Weather Index (FWI) System; developed over several decades of solid forestry research in Canada**
- **Using FWI, model the forest fire detection as a *k*-coverage problem**
  - **Present a distributed *k*-coverage algorithm**
- **Present data aggregation scheme based on FWI**
  - **Significantly prolongs network lifetime**
- **Extend the *k*-coverage algorithm to provide unequal coverage degrees at different areas**
  - **E.g., parts near residential area need more protection**

The Fire Weather Index (FWI) System



- **Forest soil has different layers**
  - **Each provides different types of *fuels***
- **FWI estimates moisture content of fuels using weather conditions**
  - **and computes indexes to describe fire behaviour**

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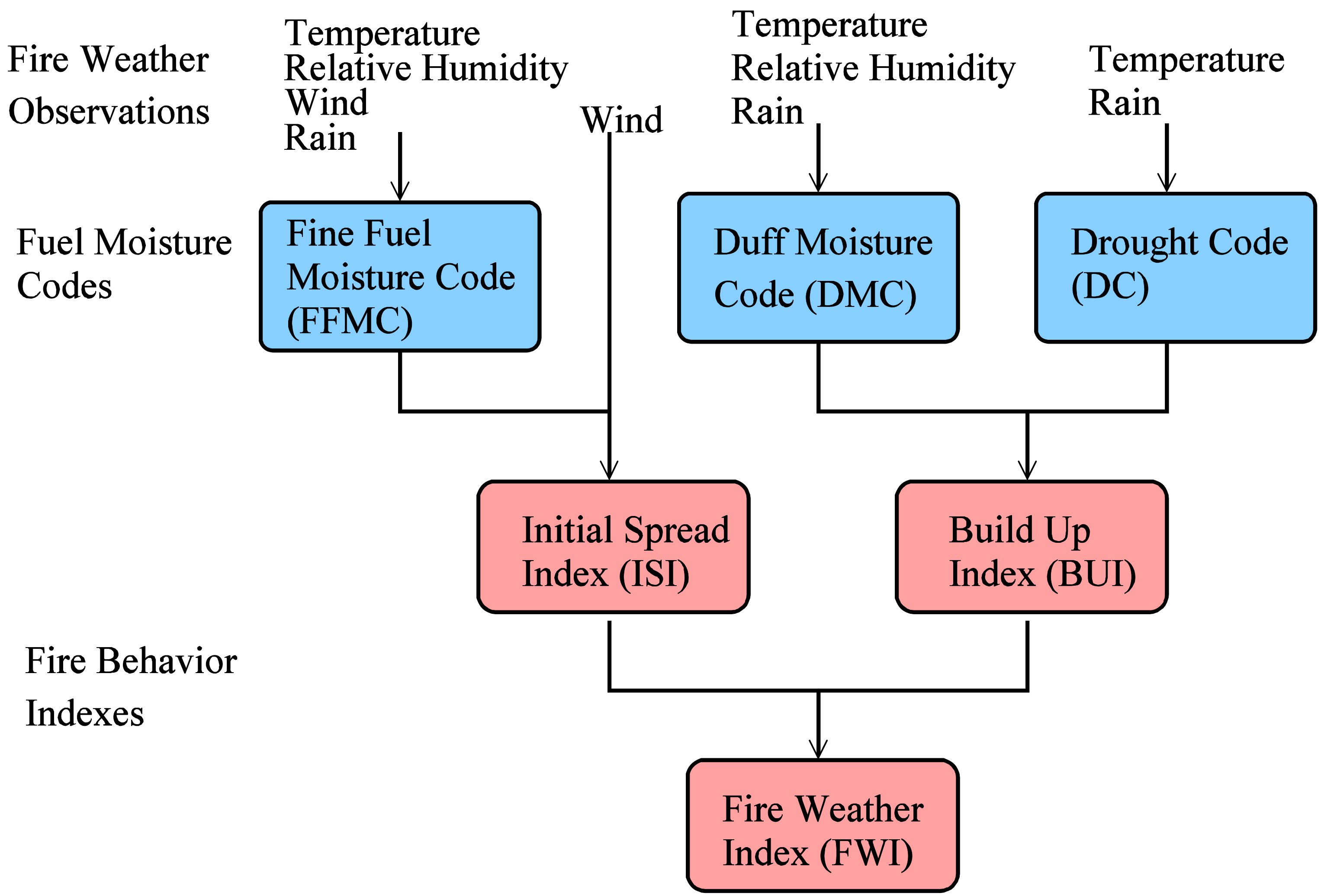
FWI Structure



FWI: Two Main Components

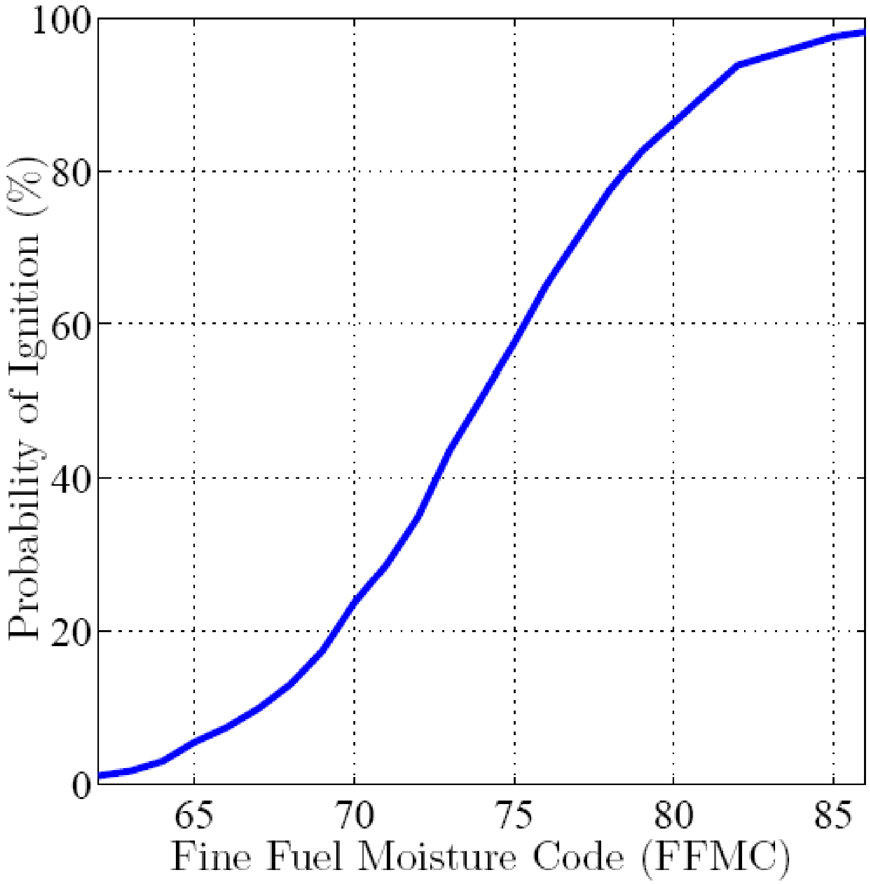
- **FFMC: Fine Fuel Moisture Code**
  - **Indicates the ease of ignition of fuels**
  - **➔ can provide early warning of potential fires**

- **FWI: Fire Weather Index**
  - **Estimates the fire intensity**
  - **➔ can imply the scale and intensity of fires if they occur**

- **Verification in the following two slides**

FFMC vs. Probability of Ignition

- **Data interpolated from [de Groot 98]**
- **Fires start to ignite around FFMC = 70**



FWI index vs. Fire Intensity

FWI = 14

FWI = 24

FWI = 34

- Pictures from experiments done by Alberta Forest Service; re-produced with permission

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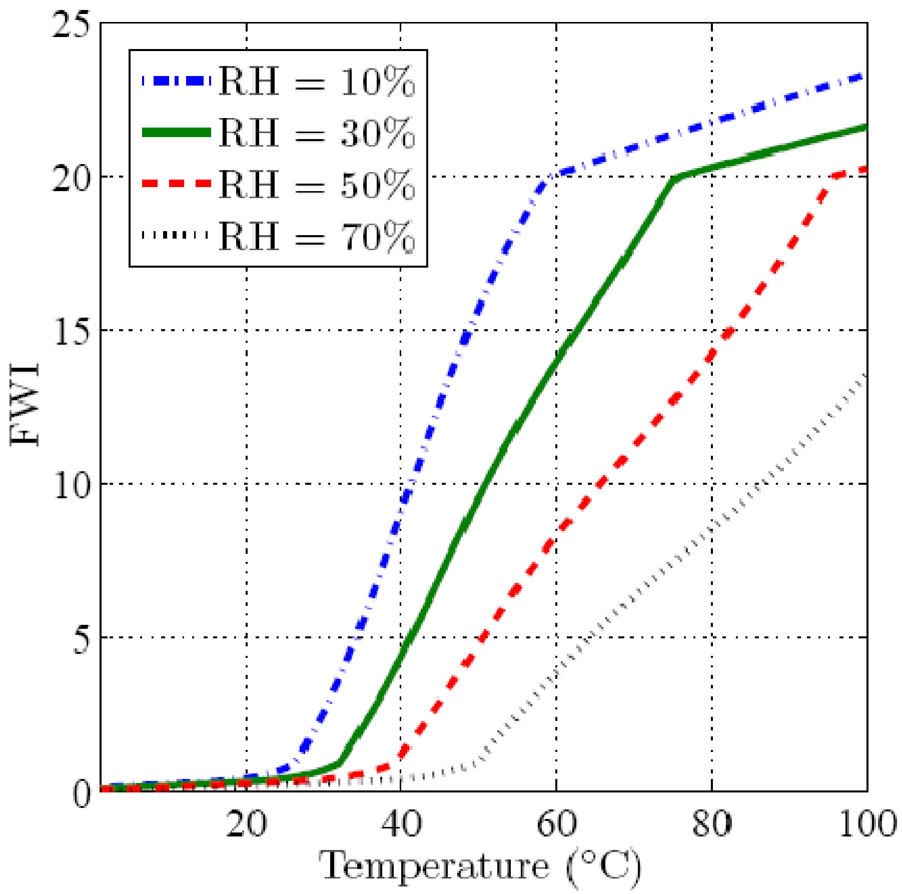
WSN for Forest Fires

- **Two Goals**
  - Provide early warning of a potential fire
  - Estimate scale and intensity of fire if it materializes
- **Our approach**
  - Use FFMC to achieve first goal, and FWI for the second
  - Both FFMC and FWI are computed from basic weather conditions: temperature, humidity, wind, …
  - Sensors can collect these weather conditions
  - Accuracy of data collected by sensors impacts accuracy of computing FFMC and FWI
  - Quantify this accuracy and design WSN to achieve it

Sensitivity of FFMC and FWI to Weather Conditions

- **Accuracy at high temperature and low humidity is critical (steep slope)**
  - **Manufacturers could use this info to customize their products for forest fire applications**
- **Given maximum allowed errors in estimating FFMC and FWI, we can determine the needed accuracy to collect weather conditions**



- **Equations and code for computing FFMC and FWI obtained from Canadian Forest Service**

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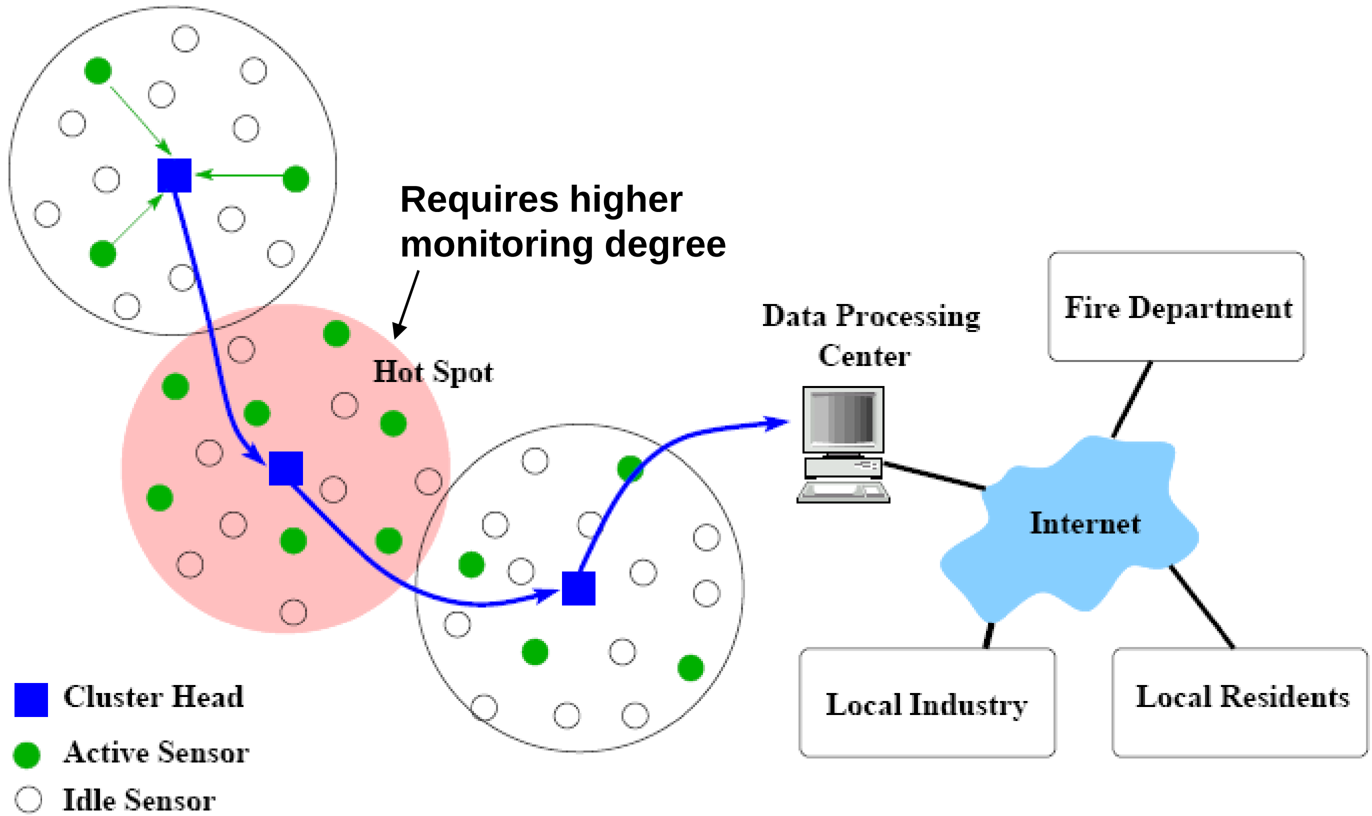
Architecture of WSN for Forest Fires



- **Sensors randomly deployed in forest, self-organize into clusters**
  - **clustering protocols are orthogonal to our work**
- **In each cluster, subset of nodes are active and report weather conditions to their head**
- **Data Aggregation: Heads compute FFMC and FWI and forward them, not the raw data**

Forest Fire Detection as Coverage Problem

- Consider measuring temperature in a cluster
- Sensors should be activated s.t. samples reported by them represent temperature in the whole cluster
  - ➔ cluster area should be covered by sensing ranges of active sensors (area 1-coverage)
- In forest environment, sensor readings may not be accurate due to: aging of sensors, calibration errors, …
  - ➔ may need multiple sensors to measure temperature (*k*-coverage)
- When nodes are dense (needed to prolong lifetime), area coverage is approximated by node coverage [Yang 2006]
  - ➔ area *k*-coverage ~= point *k*-coverage

Forest Fire Detection as Coverage Problem

- **Coverage degree *k* depends on reading accuracy of individual sensors σ_T and tolerable error δ_T:**

$$k = \left\lceil \left(z_{\frac{\alpha}{2}} \frac{\sigma_T}{\delta_T} \right)^2 \right\rceil$$

  - **Details are given in the paper**

- **Trade off between *k* and sensor accuracy**
  - **Quantified in the experiments later**

k-Coverage Protocol

- **Knowing *k*, we need a distributed protocol that activates sensor to maintain *k*-coverage of clusters**
  - **Proposed in our previous work [Infocom 07] and extended in this work to provide unequal coverage at different sub-areas**
- **Unequal coverage is important because**
  - **some areas are more important than others (residential)**
  - **fire danger varies in different regions ➔**

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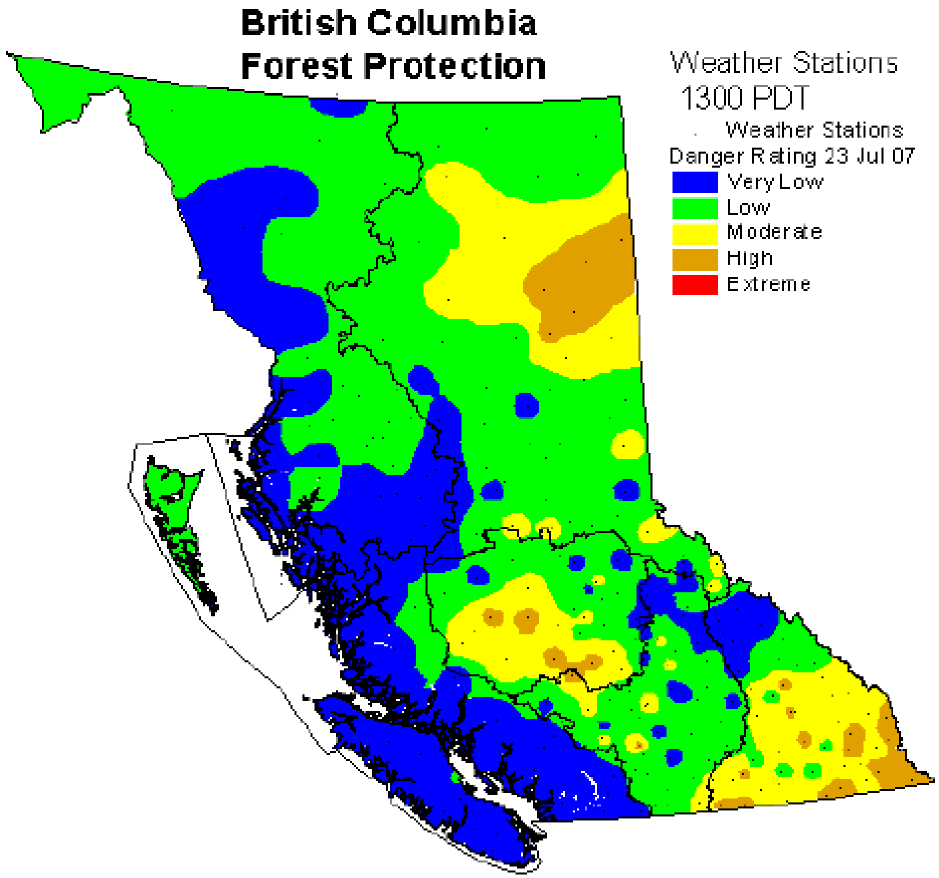
Importance of Unequal Coverage

- Real data;
- Re-produced with permission from BC Ministry of Forests and Ranges



- Notice high danger spots within moderate danger areas

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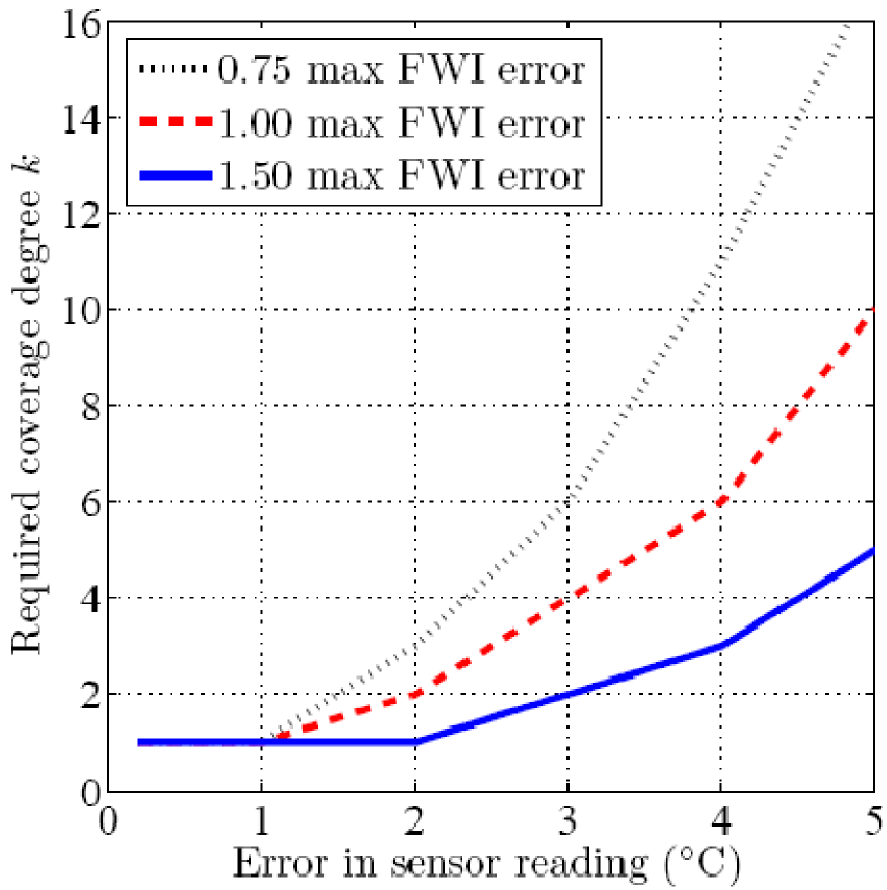
Evaluation

- Using simulation and numerical analysis to:

- Study trade off between *k* and sensor accuracy
- Analyze errors in FFMC and FWI versus *k*
- Show unequal coverage can be achieved
- Study network lifetime and load balancing

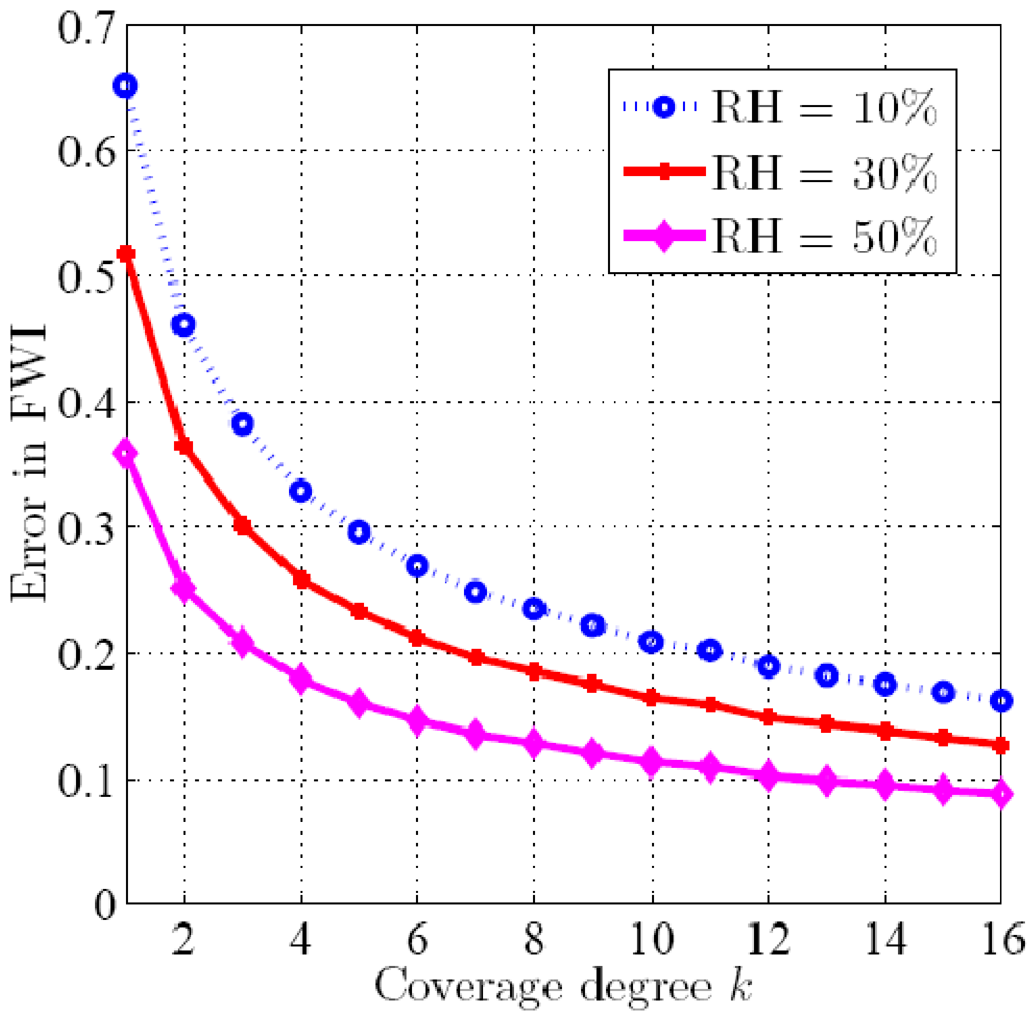
- Only sample results are presented; see the extended version of the paper

Required *k* vs. Sensor Accuracy



- **Cheaper (less accurate) sensors → need to deploy more of them**

Errors in FWI vs. *k*



- **Error in FWI is amplified in extreme conditions ➔ re-configure network as weather conditions change**

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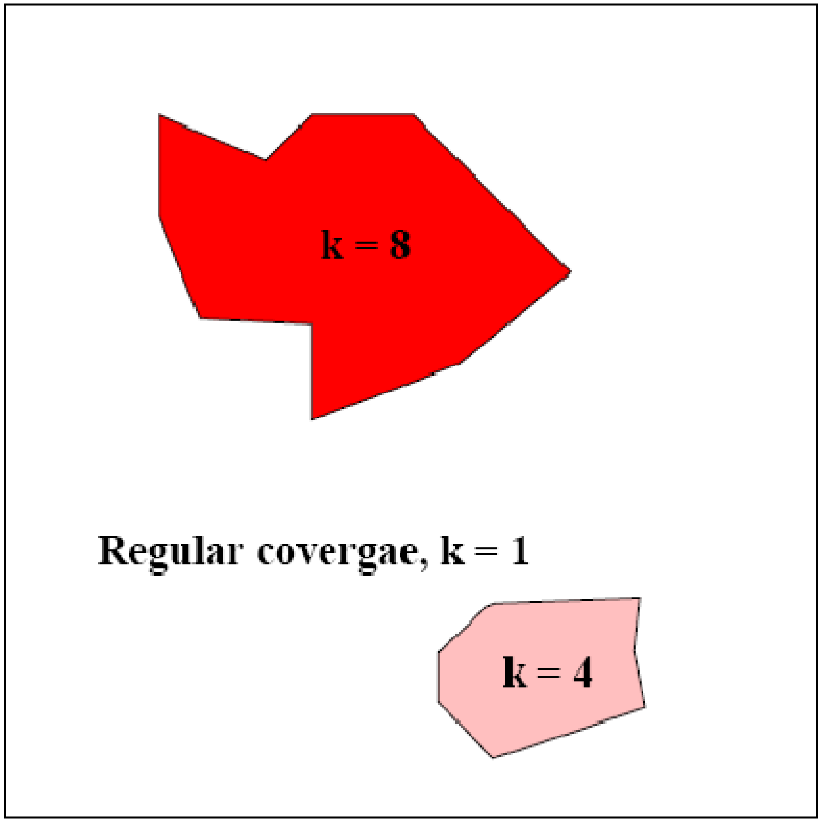
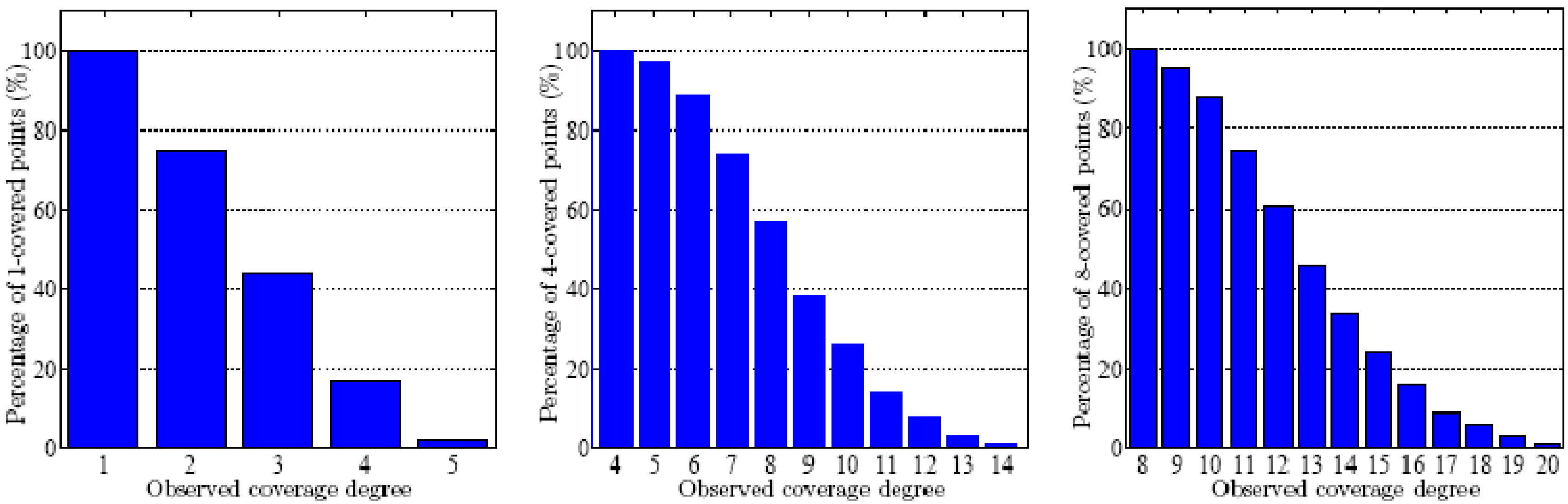
Unequal Coverage

- Simulate a forest with different spots
- Run the protocol and measure the achieved coverage



Unequal Coverage (cont'd)



(a) Requested $k = 1$ (b) Requested $k = 4$ (c) Requested $k = 8$

- **Different areas are covered with different degrees**

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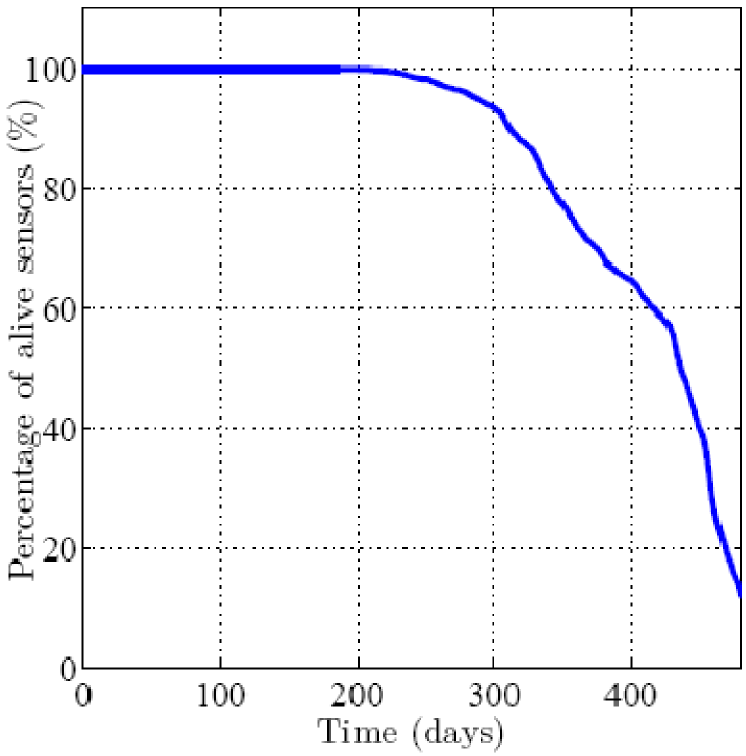
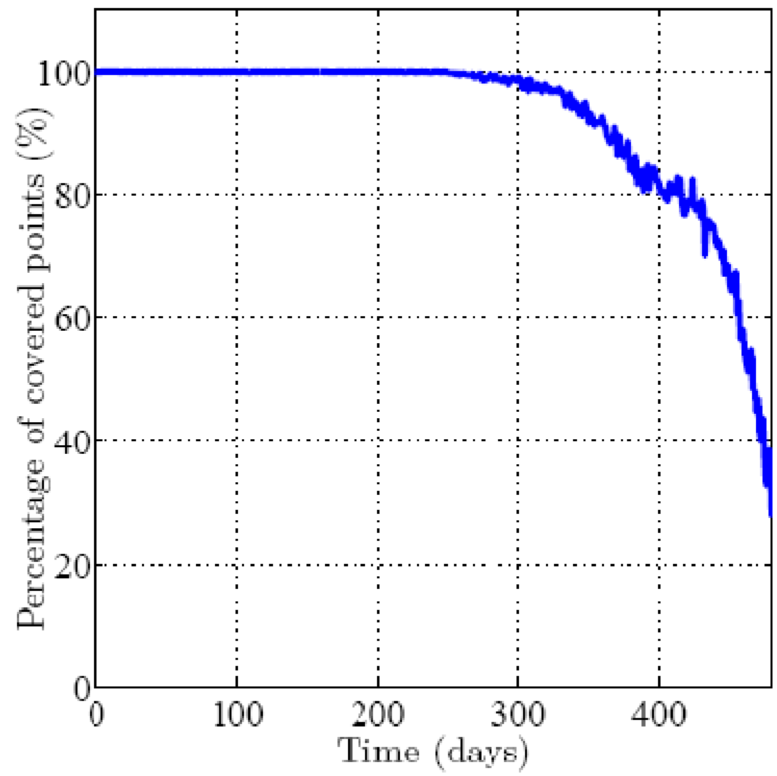
Network Lifetime and Load Balancing





- **Most nodes are alive for long period, then they gradually die**
- **Coverage is also maintained for long period ➔**
- **Load is balanced across all nodes**

Conclusions

- Presented the key aspects of forest fires using
  - The Fire Weather Index (FWI) System
- Modelled forest fire detection as *k*-coverage problem
- Showed how to determine *k* as a function of sensor accuracy and maximum error in FWI
- Introduced the unequal coverage notion and presented a distributed protocol to achieve it

Thank You!

Questions??

- **Details are available in the extended version of the paper at:**

http://www.cs.sfu.ca/~mhefeeda